



*S.O.M. HIGH RISE*  
*COLLABORATORY*

Winter & Spring 2020

CAED

California Polytechnic  
State University, San Luis Obispo

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**KNOTTED TUBES**

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## **INTRODUCTION**

Skidmore, Owings, & Merrill (San Francisco Office) partnered with Cal Poly's College of Architecture and Environmental Design to host two-quarter long high rise interdisciplinary design studio. The studio would be made up of 3<sup>rd</sup> year architecture majors, 4<sup>th</sup> year ARCE majors, as well as a few ARCE Master's students, all working together in teams of three or four architecture and ARCE majors. Each of the total ten teams (nine in winter) would come up with a unique design for a 700 – 800 foot tall residential high rise building based on an initial typology or theme. Below is a list of some of the final properties and building information for Knotted Tubes, the only given information being the site location and building type, and the rest resulting from the evolutionary stages of the project.

Site Location: **15 Oak Street, San Francisco, CA, 94102**

Building Type: **Residential**

Height: **800'**

Max Plan Dimensions: **165' x 90'**

Avg. Floor Area: **10,725 sf**

Typical Clear Story Height: **12.5'**

Number of Stories: **64**

Avg. Housing Area: **7,000 sf**

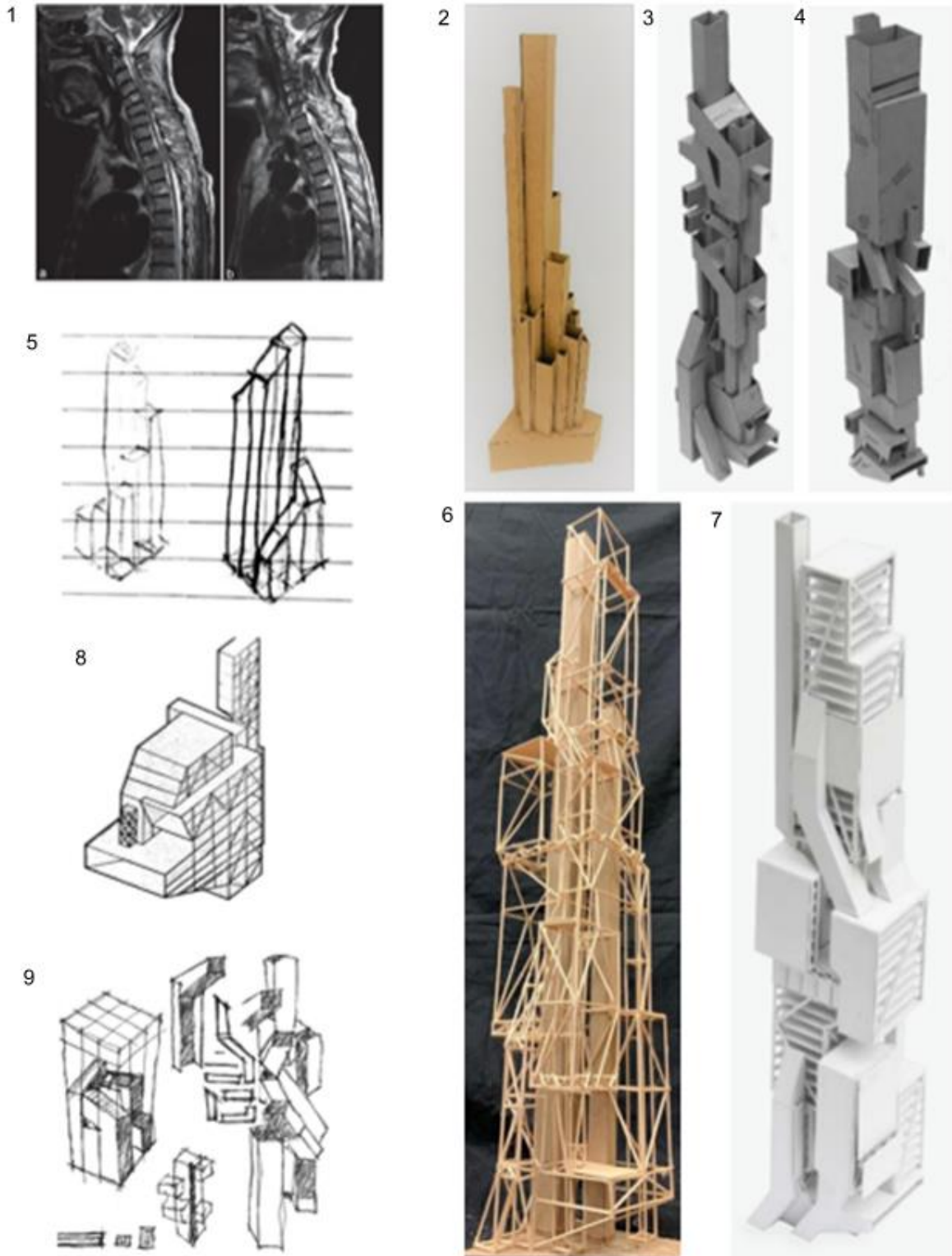
Starting Typology: **Bundled Tubes**

## **NARRATIVE**

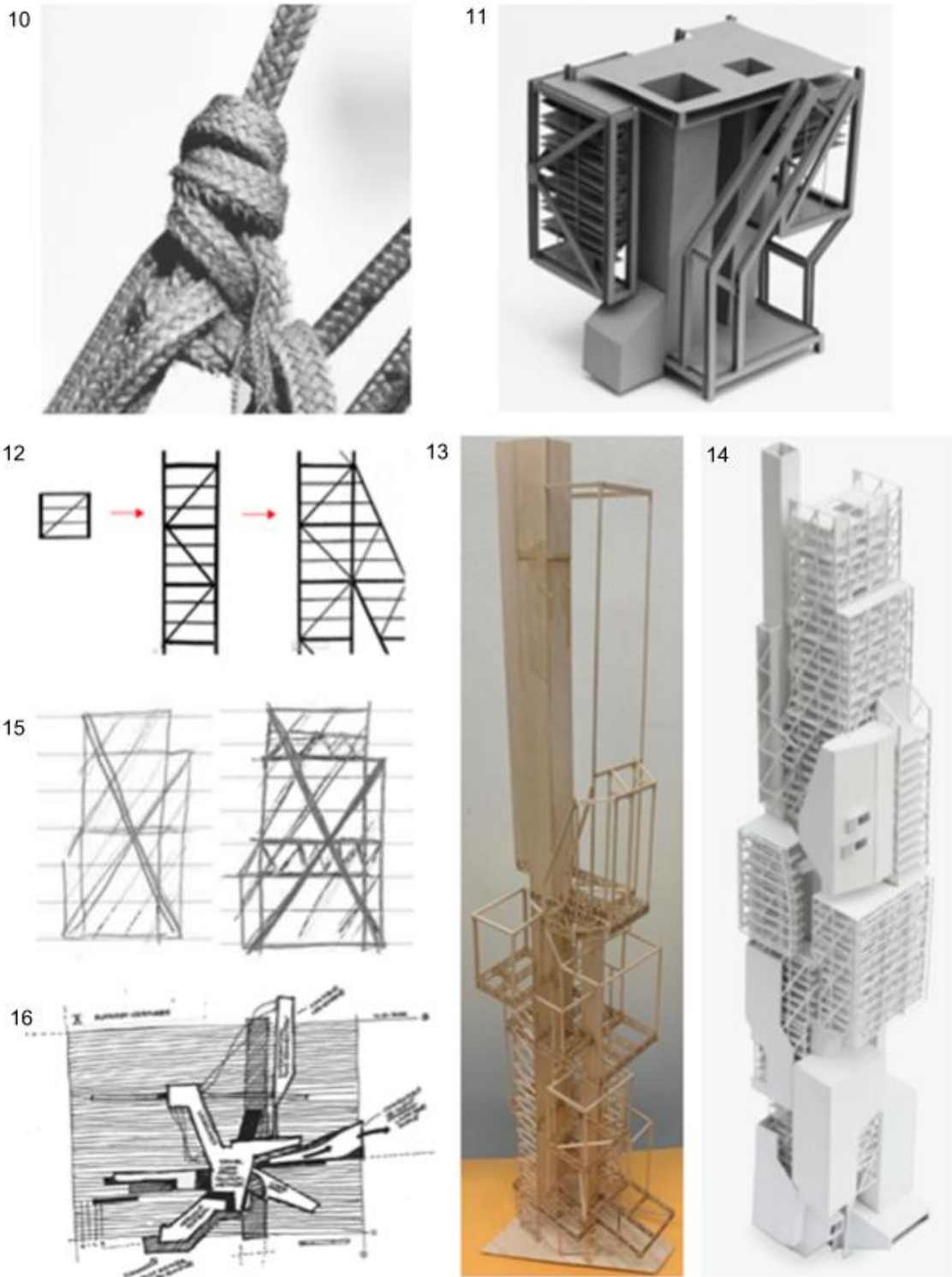
The initial design typology for our building was focused on bundled tubes, which is already a well-known structural system that has been in use for tall buildings since its invention in 1973 with the Willis Tower (formerly Sears Tower). In the preliminary design phases in studio of our tower, we explored some iterations of form that were similar in nature to a typical bundled tube system. Though, we soon began to challenge the concept of how a typical bundled tube building can work, generating more dynamic forms with different shapes and orientation of tube, deviating from the usual straight vertical nature of the bundled tube. From these early design phases, the narrative of the structure developed, initially centered on the idea of a spinal cord and nervous system, and how it is has a central pathway that branches out and converges into moments of intensity in the body, entangled with the solid skeletal system.

Moving forward through winter quarter, we began to further explore what those moments of intensity could be, then fixating on the idea of a knot, like a knotted rope. The idea of the building was reimaged and evolved into a bundled tube structure in which the tubes would either separate to form a void space or entangle to form a "knot", with the void spaces and knots serving both vertical community programming and structural purposes. At this stage, during the end of winter quarter, the building had a primary void space that served as a "(k)not", as well as multiple braced frame lines that formed tubes adjoined to the two structural cores, and many outrigger and gravity trusses for the gravity system.

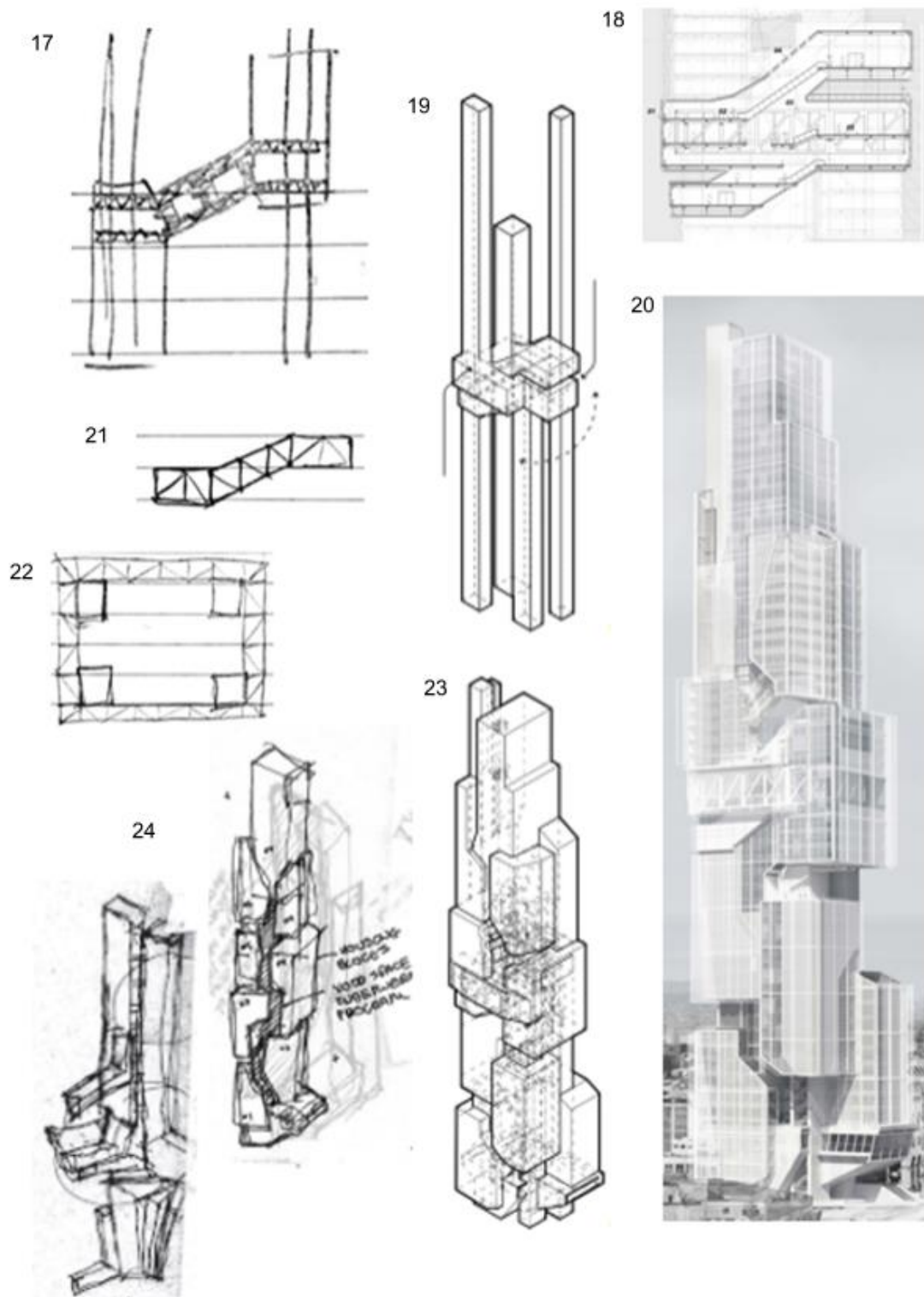
Moving into winter, we wanted to reimagine what the "knot" of the structure could be, moving away from the concept of a void space where the structure separates to instead a point of convergence of the structural system. At this convergence, the primary tectonics of the building would mesh and entangle at one location, which would also lead to an intersection of the programming and vertical community spaces. This idea led to a "knot" at around mid-height of the tower where the primary lateral and gravity trusses meshed with the now four separate cores, but arranged in a fashion that allowed for program and circulation to intersect the space, creating a beautiful marriage of structure and function. The knotting of the cores (or tubes) became the final culmination of the narrative over both quarters.

"Bundled Tubes"

**Fig. 2.1** – (1) Spinal Cord X-Ray images; (2) “traditional” Bundled Tube form-finding model; (3) “Vape” form-finding model; (4) “Small Tobacco” form-finding model; (5) Dynamic tube bundle brainstorming sketches; (6) Preliminary structural framing model; (7) Early architectural model with set form; (8) Podium column and bracing layout brainstorm sketch; (9) Dynamic tube shape and orientation brainstorming sketches.

"Bundled Knots"

**Fig. 2.2** – (10) Knotted Rope image; (11) Void Space / Vertical Community physical model; (12) Braced Frame / Tube diagonal intersection diagram; (13) Final (unfinished) structural framing model of winter quarter; (14) Final architectural model including exterior framing; (15) Multistory diagonal bracing scheme w/ outriggers brainstorming sketches; (16) "Knot" concept sketch (void or solid intersection?)

"Knotted Tubes"

**Fig. 2.3** – (17) Preliminary space frame brainstorm elevation sketch, figuring out how to connect cores; (18) Final architectural section of knot space; (19) Axon drawing showing primary configuration of cores and knot entanglement; (20) Final 3D rendering of Knotted Tubes; (21) Diagonal truss configuration for connecting core walls; (22) Plan view of idealized core connection, brainstorm of space frame trusses wrapping around cores; (23) Final Axon drawing of building form with core configuration axon inside; (24) Form brainstorming sketches.



## DESIGN

### PHYSICAL STRUCTURAL MODELS:



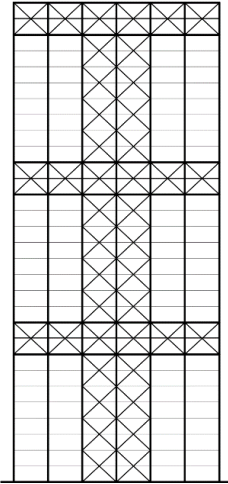
Above can be seen many of the iterations of physical structural framing models, along with the last architectural model made during winter quarter which shows a lot of structure on the exterior. The structural models are made primarily of basswood sheets, basswood sticks, or applicator sticks, which worked well in conveying the idea of the structural system, even when the system wasn't perfect or fully flushed out yet. Between each iteration, many design changes were made for both the form and function of the building that led to changes in the structural system, as well in changes of the structural system that also changed the form. The models served as tools for mapping and figuring out the intricacies of the systems and how they relate to the form, in addition to conveying the idea of the structure and how it worked to others, including the architects on my team.

Also, during both quarters, rudimentary calculations were sometimes performed to generate typical loads and forces to be used to size structural members or generate a load path through the system. Some calculations were repeated during different stages of design to account for changes in design assumptions or building form or system. One example of these crude calculations for uniform wind loads can be seen to the left, affectionately called "back-of-napkin" calculations.

HIGH RISE PROPOSAL LATERAL LOADS

LOCATION: 1500 MARKET ST., SAN FRANCISCO, CA  
 SITE CLASS = D (DEFAULT)  
 RISK CATEGORY III HEIGHT = 800'

WIND  
 $V = 100 \text{ mph} (43 \text{ m/s})$   
 SURFACE ROUGHNESS: B → EXPOSURE CATEGORY B  
 $K_d = .85 (T 26.6-1)$  (T 26.11-1)  $z_g = 1200'$   
 $K_{zt} = 1.0 (26.9.2)$   $\alpha = 7.0$   
 $K_e = 1.0 (T 26.9-1)$   
 $K_z (15' \leq 800' \leq 1200') = 2.01 \left( \frac{z}{z_g} \right)^{2.5}$   
 $= 2.01 \left( \frac{800}{1200} \right)^{2.5} = 1.79 (T 26.10-1)$   
 $q_z = .00256 K_z K_{zt} K_d K_e V^2 \text{ (psf)} (26.10-1)$   
 $= .00256 (1.79)(1.0)(.85)(1.0)(100 \text{ mph})^2$   
 $= 38.93 \text{ psf} \sim \underline{39 \text{ psf}} @ 800'$

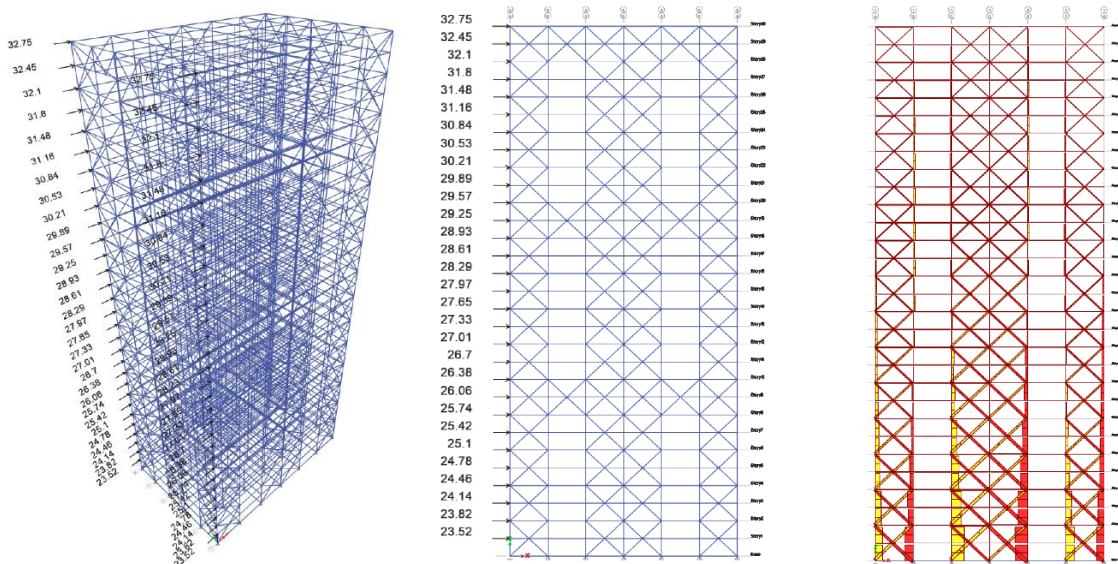


## ANALYSIS

The structure went through many iterations and changes during its evolution to the current system shown today, and many of those changes were fueled by more than just architectural design changes or form polishing. To fully understand how to design the structural system of a tall building such as this, some analysis studies needed to be performed to explore the behavior and combination of different types of lateral force resisting systems. These analyses were conducted using computer software like RISA 2D or ETABS. Some initial studies were conducted in winter quarter of simple structures to explore the basics of simple structural systems applied to tall structures, as well how certain components aid in the behavior of the system. Later studies in the spring built upon the same concepts, adding emphasis on dual systems and how changing properties or configurations of elements affected the system's performance. Finally, the lessons learned from these studies fueled the evolution of the structure of our tower, and were applied to analysis models of the building being designed. Below are some rough overviews of most of the studies performed.

### INITIAL STUDIES (Winter):

#### 30-STORY STEEL BRACED FRAME

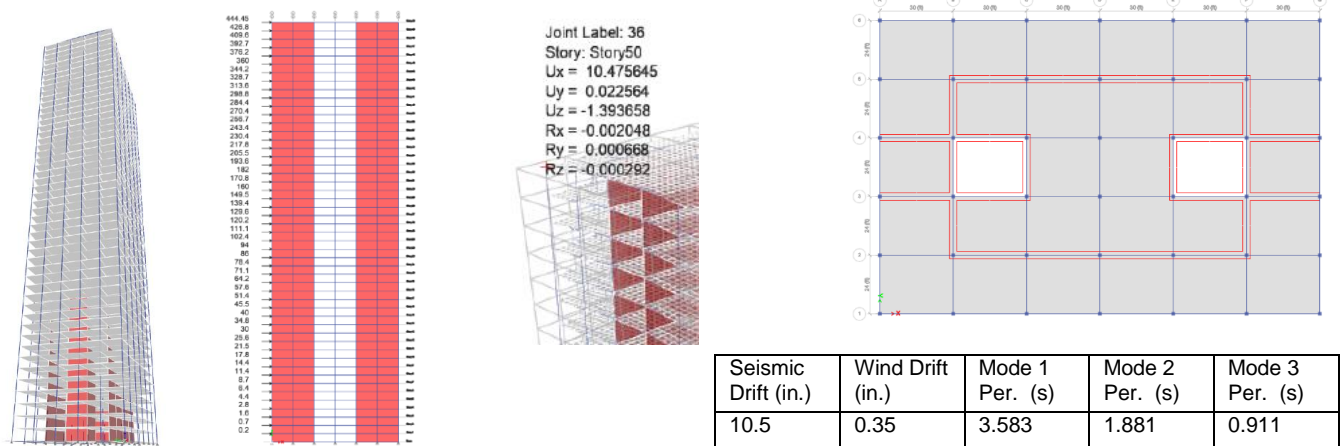


**Fig. 4.1** – (Left) 3D View of ETABS model w/ loads applied to exterior frames; (Middle) Elevation of final iteration with two-story outriggers and same loads applied; (Right) Axial force diagram of earlier iteration without outriggers.

floor included a final deflection of 14.4", which was over the established drift limit of  $H/500$ , and the axial forces were found to be greatest in the outrigger columns and outrigger diagonal braces. The addition of outriggers into the final iteration had the largest effect on the drift of the model, due to the nature of an outrigger truss in extending the footprint of the lateral system with the outer columns that transfer truss forces to the foundation. In this case, the outriggers also stiffened the system by connecting the multiple bays of braced frames at multiple locations, forcing them to deflect and resist forces together.



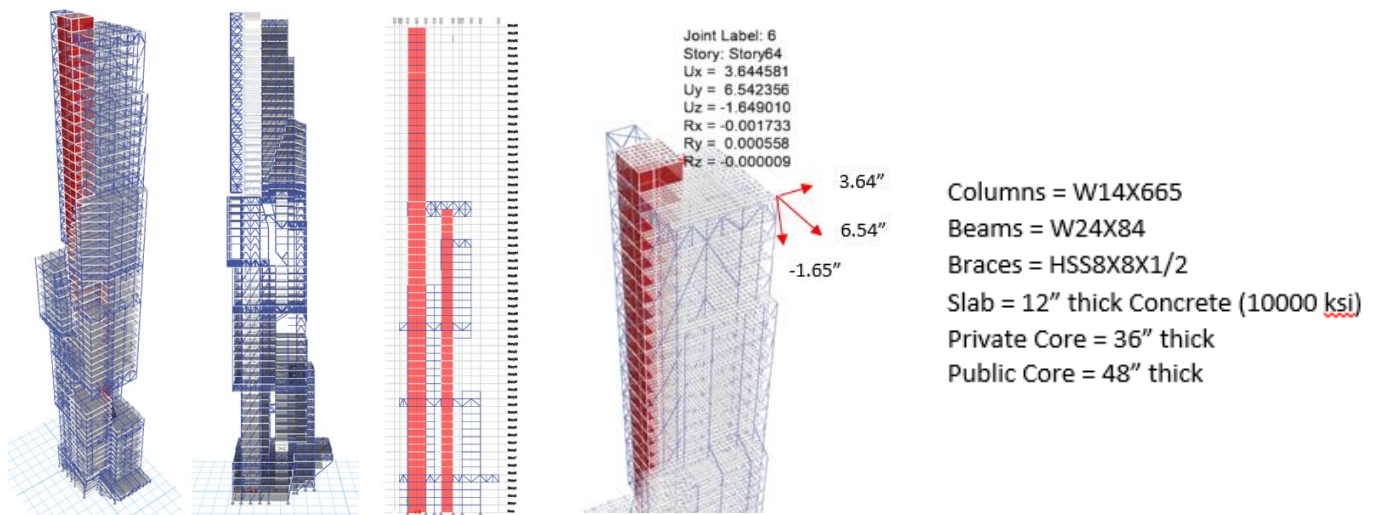
## 50-STORY CONCRETE



**Fig. 4.2** – (Left) 3D View of ETABS model; (Mid-left) Elevation of interior grid line with shear wall cores and seismic loads applied; (Middle) Snip of Joint displacement at top of structure due to seismic loading; (Right-top) Plan view of ETABS model showing shear wall layout; (Right-bottom) Table showing drifts from seismic and wind loading, and periods of first three mode shapes.

**RESULTS / LESSONS LEARNED:** The final iteration of the 50 story concrete shear wall model included 36" thick shear walls, but in a layout that encompassed much of the floor area to get the drift under the limit. The reason that so many shear walls were needed to get the drift under limit was that code seismic forces from ASCE 7-16 were applied to the building, which, at a height of 600', were way too massive to be considered realistic for this system. The magnitude of the seismic forces were so large because of the factor  $k$  applied to the equation  $w^*(h^k)$ , used to determine vertical distribution of forces. However, the factor was incorrectly applied to only the numerator of the equation, which resulted in forces much larger than actual.

#### FIRST ATTEMPT AT BUILDING (Winter):



**Fig. 4.3** – (Left) 3D View of ETABS model; (Next to Left) Side-oriented 3D view; (Mid-Left) Interior wall line section showing shear walls and outriggers; (Mid-Right) Joint displacement at top of structure under gravity loads; (Right) Framing and wall sizes and properties.

**RESULTS / LESSONS LEARNED:** The model made to represent the structure at the end of winter quarter was much too complicated to properly represent how the structural system worked, and resulted in strange deflections under only gravity loads, showing many issues with the current design. To address these issues in spring, the top shape needed to be more centered on the plan, and more continuity needed to be established through the form to get better load transfer to the foundation, as well as possibly rearranging or adding more cores.

MORE STUDIES (Spring):

DUAL SHEAR WALL / MEGA-FRAME SYSTEM

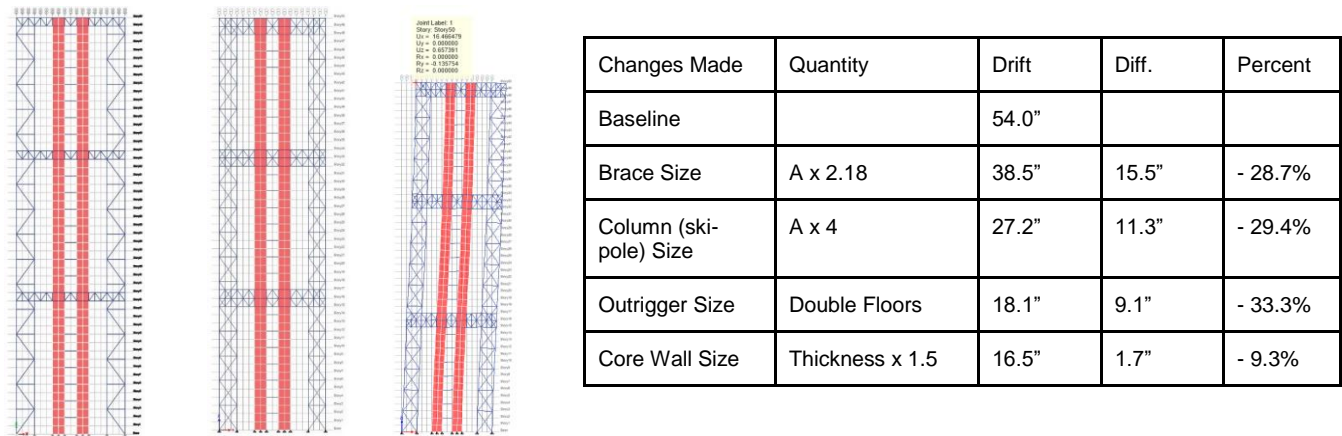


Fig. 4.4 – (Left) Elevation of first iteration of ETABS model; (Next to Left) Elevation of last iteration of ETABS model; (Middle) Deflected Shape with joint deflection of final iteration under wind loading; (Right) Table showing changes in design of system and the results.

**RESULTS / LESSONS LEARNED:** The first study of spring quarter focused on dual systems, and in this case included shear walls coupled with a mega-frame (with outriggers as beams and vertical frames as columns), with the primary takeaway being that the outriggers provided the most stiffness when coupled with shear walls. This is due to the fact that the outriggers essentially widen the stance of the slender shear walls when they span from the walls to the outermost columns, so that both the slender walls and mega-frame act together to resist deflection.

FINAL STUDIES (Spring):

SIMPLIFIED CORE / KNOT SYSTEM

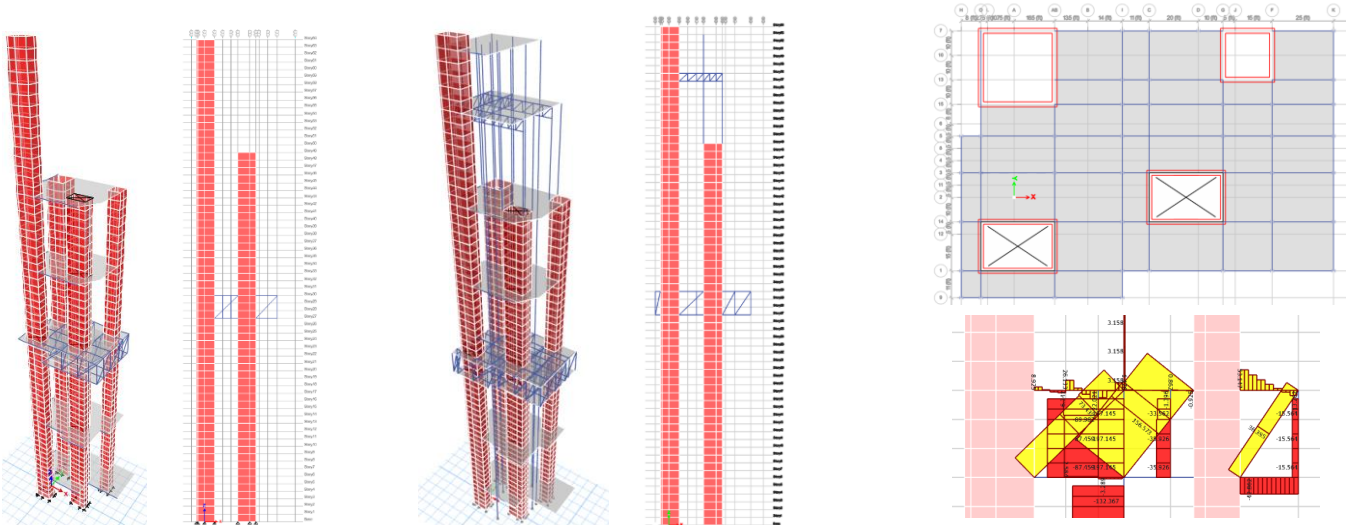
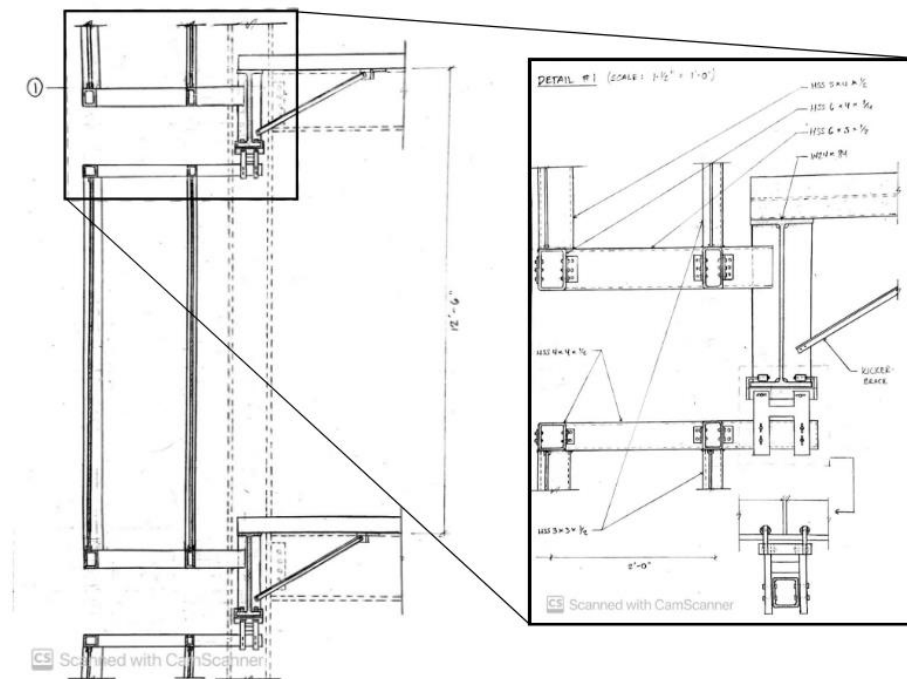


Fig. 4.5 – (Left) 3D View of first simplified iteration and primary line section showing walls and truss; (Middle) Final iteration 3D view and section of interior line; (Right-top) Knot Plan layout; (Right-bottom) Axial Forces in one line of knot trusses.

**RESULTS / LESSONS LEARNED:** The final model of our building was much more simplified and streamlined to better represent how the system worked, and resulted in drifts in both principal directions under the limit (9.6" E-W, 12.3" N-S) and forces in the knot trusses that could generate somewhat reasonable framing member sizes. The first three mode shapes were N-S translation (4.5 s), E-W translation (3.6 s), and rotation (1.2 s). This final iteration included trusses, rigid diaphragms, continuous and discontinuous columns, and four shear wall cores 24" thick.

## PERFORMATIVE ENVELOPE

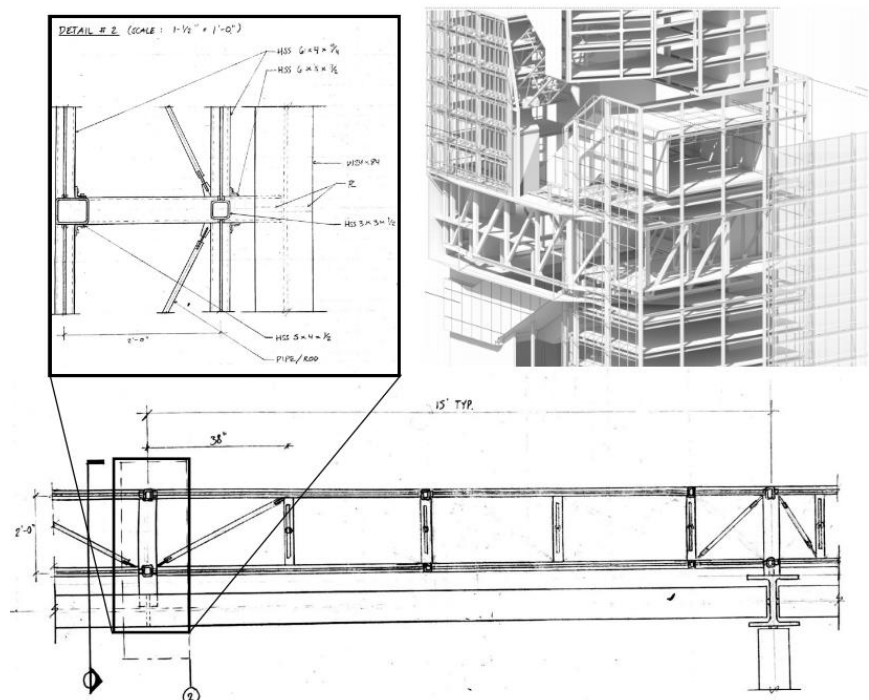


**Fig. 5.1** – Elevation view (left) and Elevation Section Detail (right) of typical double-skin framing connection to girder.

which allow for both shading and outward visibility with different orientation of the louvers, which can be rotated by means of a mechanism.

The framing of the double-skin is comprised of rectangular HSS steel tubes, and is segmented per floor, as can be seen in Fig. 5.1. The framing is supported by a cantilevered tube welded to the exterior girder on bottom, and a smaller tube attached to the bottom of the girder above with a roller/slotted pin mechanism (Fig. 5.1). This mechanized connection is what allows for the frame to move independently of the floor above it, to account for inter-story drift, vertical deformation of columns, and construction tolerances.

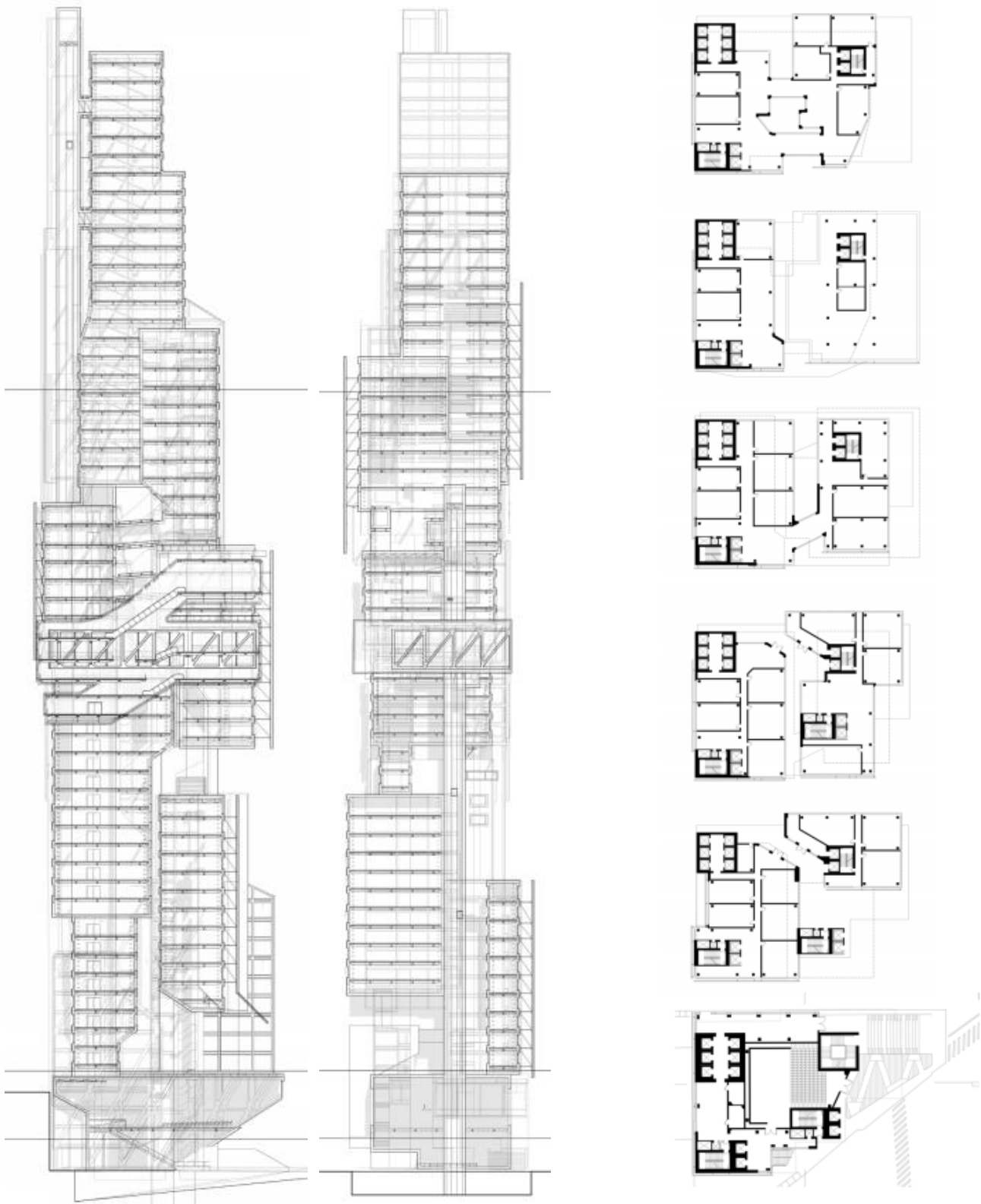
Fig. 5.2 shows a plan view and section of the assembly, with steel pipes making up the horizontal bracing of the framing, and HSS tubes as mullions and structural framing members.



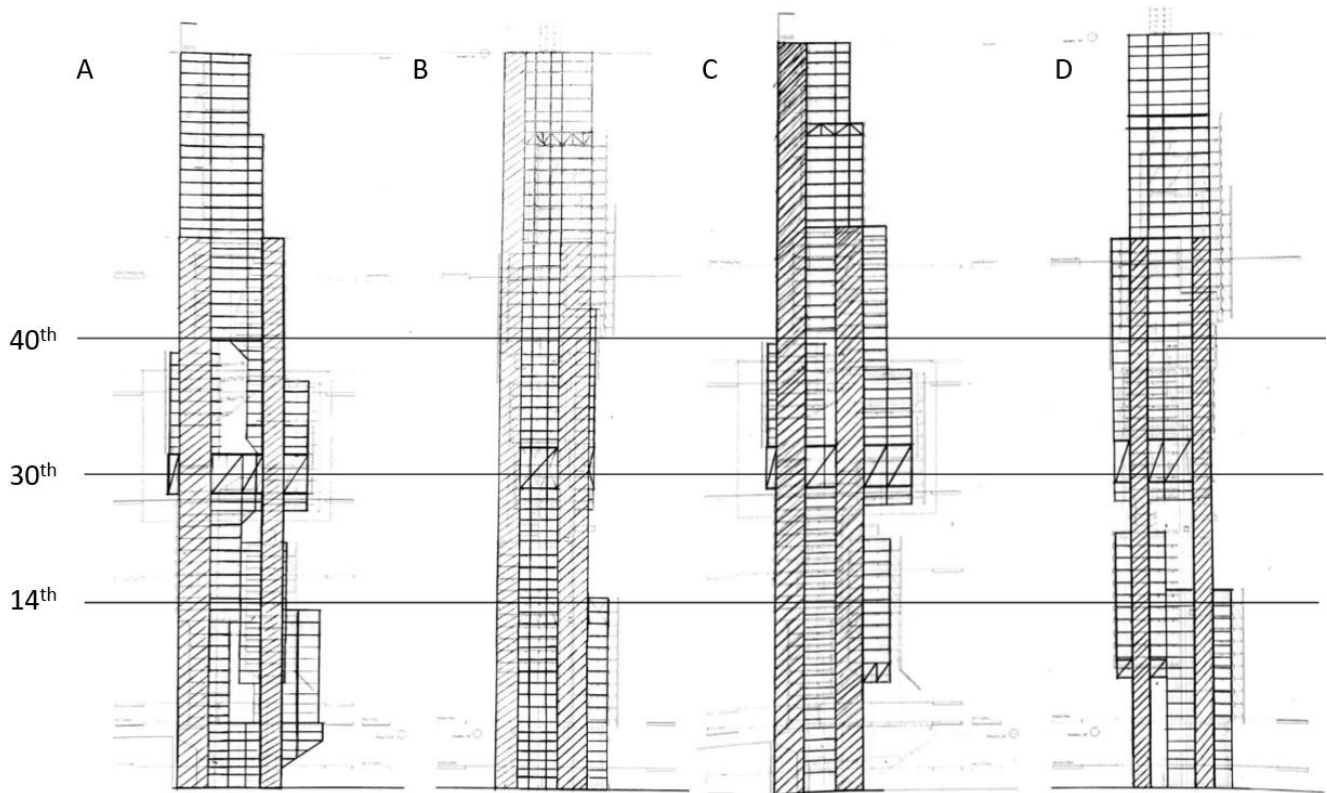
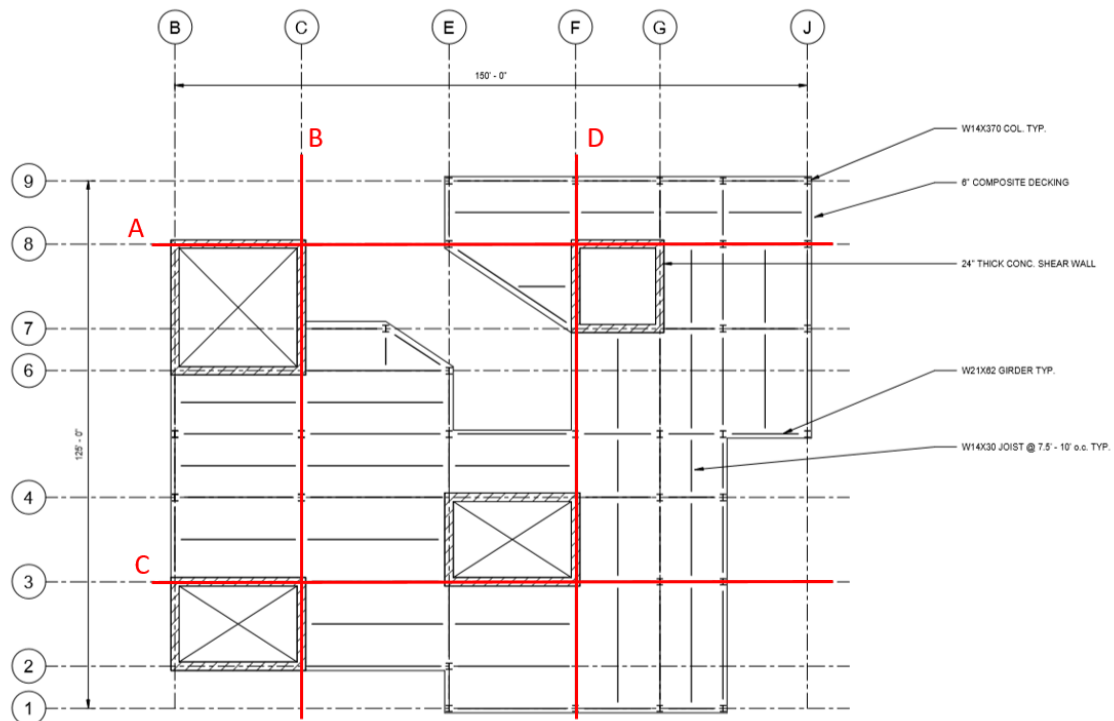
**Fig. 5.2** – Plan view (bottom) and Plan Section Detail (top-left) of typical double-skin framing connection to girder, and 3D rendering of envelope system on exterior of building (top-right).

## PLANS & SECTIONS

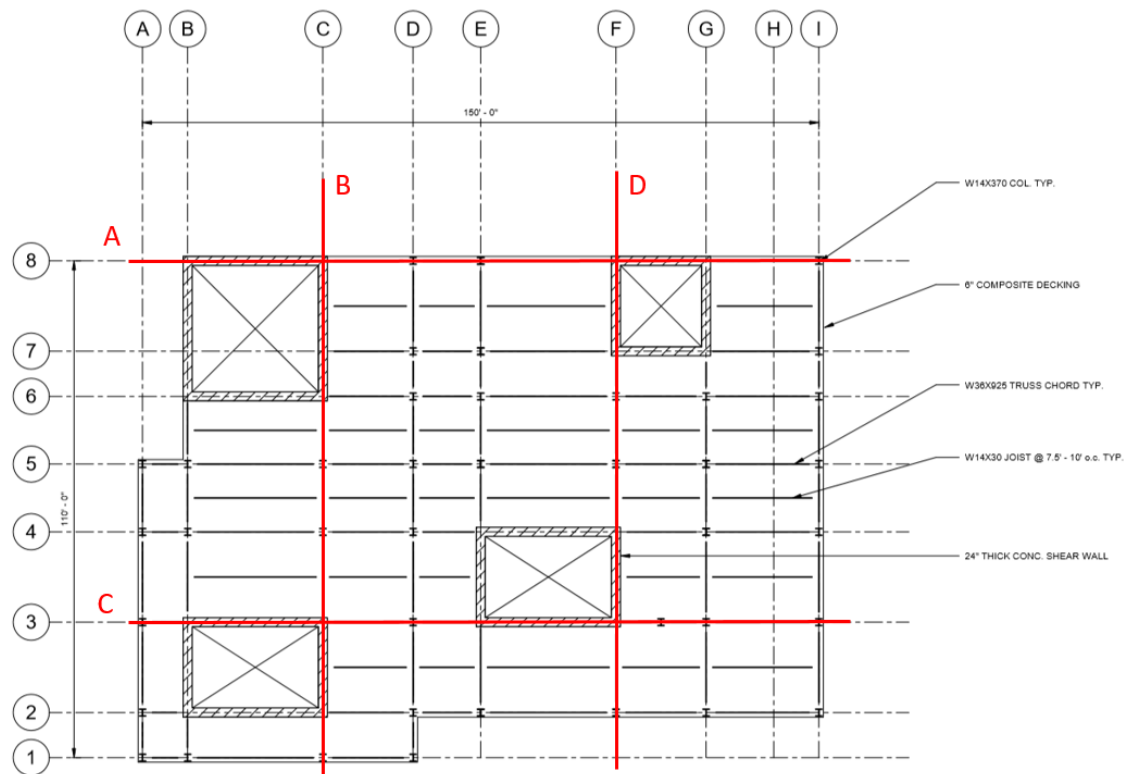
### ARCHITECTURAL PLANS/SECTIONS:



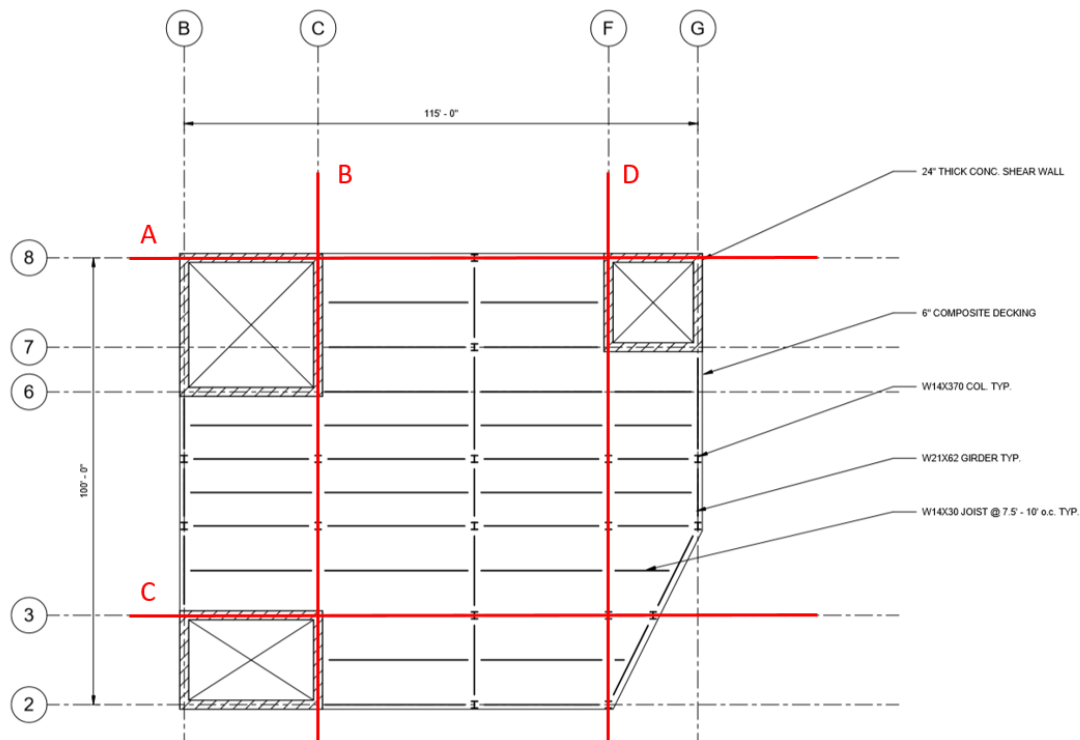


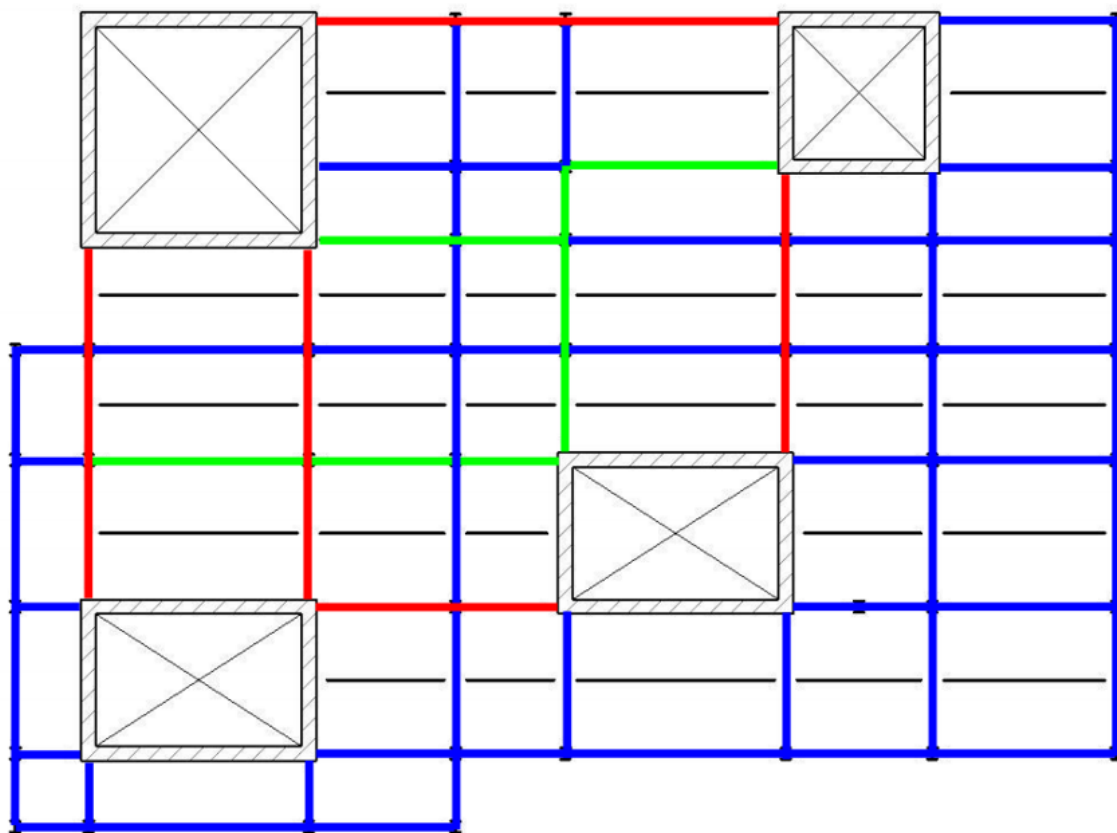
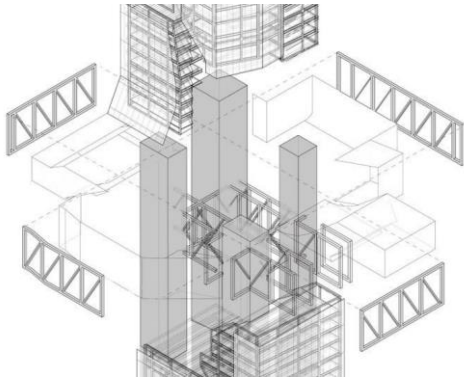
STRUCTURAL SECTIONS:14<sup>TH</sup> FLOOR:

30<sup>TH</sup> FLOOR:



40<sup>TH</sup> FLOOR:



KNOT TRUSS DIAGRAM (30<sup>th</sup> & 27<sup>th</sup> FLOORS):

The “Knot” consists of three main types of trusses that each serve different, but sometimes shared, purposes. The belt trusses (red) that run in between core shear walls in line with each other, and the outrigger trusses (green) that aid shear walls not sharing lines with other walls, together with the core shear walls make up the primary lateral force resisting system of the structure. The rest of the trusses present in the “knot” are gravity trusses (blue) that cantilever out from the cores to pick up discontinuous column loads and transfer them back to the cores, then to the foundations. Some columns that enter the core from above continue through and down to the foundation, and some of these act as the “ski poles” of the outriggers. “Ski-poles” refers to the columns that run vertically down to the foundation from the ends of the outrigger trusses, primarily loaded in axial tension or compression from the outrigger trusses they support, transferring lateral forces down to the foundations. In essence, they act as supporting legs of each outrigger.

<span style="color: red;">—</span>	BELT TRUSS
<span style="color: green;">—</span>	OUTRIGGER TRUSS
<span style="color: blue;">—</span>	GRAVITY TRUSS

## CONCLUSIONS

After two full quarters of participation in SOM's High Rise Collaboratory, I learned more about high rise residential design than I did during the first four years I spent in Cal Poly's ARCE undergraduate program, which isn't meant to be a criticism in the slightest. Rather, I am grateful that my Graduate education in ARCE offered me the opportunity to delve into an aspect of design that I wouldn't normally, and with the aid of a prestigious firm with an impressive portfolio in that specific area of design. Now, soon to be entering the workforce with a Master's Degree in Architectural Engineering, I feel confident in my abilities as an engineer and ability to work in an interdisciplinary environment on larger projects like skyscrapers. Though I recognize that I still have much to learn and master, and that I will likely be learning and growing every day until the end of my career, I feel that this experience has given me a strong foundation with which to build a career in innovative high rise design. The collaborative nature of the studio further exposed me to the true nature of the interactions between architects and engineers in the field, and how to best navigate this collaboration to develop the best design possible.

The structure that I helped to design amazes me, because I recognize the immense amount of work put into it by my team. Each of us learned more about the other's trade, and had the opportunity to step out of our comfort zones to tackle problems and come up with solutions for aspects of design that we normally wouldn't, which is an invaluable learning experience.

This building, Knotted Tubes, is a true embodiment of the blend of structure and architecture, and how each can exist and build from each other. The form shows and celebrates the structure, while the structure incorporates and reinforces the form. Program and structural framing intersect and entangle, which supporting and emphasizing each other. The narrative of the building is driven by both the architecture and structure, with neither weighing more than the other, resulting in a stunning image that tells a riveting story of design.





